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Is microwave radiation useful for fire detection ?

Abstract

This paper deals with the question of whether microwaves might be useful for fire detection. PLANCK's law shows us that a black body emits electromagnetic radiation also in the micro- or millimeterwave region. Since such waves exhibit a different attenuation behaviour than infrared radiation an investigation of this phenomenon is interesting for a fire researcher. In this paper we will present the physical basics, explain how to measure and to use such radiation for estimation of the fire location and give some preliminary results obtained by first experiments.

1 Introduction

There are already high-tech products available on the market to locate the fire origin, or may be also persons in danger, through the smoke. Such image processing devices are based on the *infrared radiation* (IR) of a hot spot. In general, such devices are called *radiometers* since they simply measure the intensity of radiation. In the following we will distinguish between IR-radiometers and MW-radiometers where MW stands for microwaves or also for millimeter-waves. Radiometers are most commonly used for remote sensing of the earth from satellites and airplanes, but that topic is beyond the scope of this paper. In the industry, radiometers can be used for remote measurement of temperatures in ovens, converters, kilns, and other places where the use of conventional contacting temperature sensors or IR-radiometers is impossible because of high temperatures, smoke, or water vapour. However, MW-radiometers can often not compete with IR-radiometers or conventional sensors since the latters are usually cheaper and simpler to build. The main advantages of MW-radiometers for the use in fire detection are fourfold:

1. The possibility to measure through *optically thick smoke and vapor*.

2. The insensitivity of MW-radiometers to environmental conditions, such as water vapor and dust (contrary to infrared methods), and high temperatures (contrary to semiconductor sensors).

3. The fact that thermal microwave noise radiation comes from a *thicker surface layer* than the IR radiation does.

4. The fact that MW penetrates all materials except of metals.

In contrast, their main disadvantages concerning fire detection are:

1. The higher the center frequency, the more expensive are the electronic components.

2. Because of the relatively long wavelengths compared to IR, the achievable spatial resolution might be limited.

Hence, the only thing which is almost sure is that much efforts are needed to investigate whether MW-radiation can be useful for fire detection. Exactly this problem is the central topic of this paper. In the following we will present the physical basics prepared for the non-physicist, explain how to measure and to use such radiation for estimation of the fire location and give some preliminary results obtained by first experiments.

2 The physical basics

To investigate whether MW-radiation can be useful for fire detection we can split this problem into three seperate questions:

1. How much MW-power P_{E} emits a fire ?

2. How much MW-power P_{R} receives an antenna ?

3. How much MW-power P_{D} is available for detection at the antenna output ?

Before we start to answer these three questions let us shortly comment them. Of course, a theoretical analysis to predict the expected power at the antenna output is essential to judge the use of MW-radiation in fire detection. For this reason we have first to find a formula for the emitted MW-power of a fire. Obviously, since we usually not know the burned material we cannot expect to find a general formula being independent of the material properties. Fortunately, we cannot only find an upper bound but also a rough idea how much the deviation of the upper bound is. This will be explained by answering the first question. Then we consider the case of ideal transmission where we have no attenuation on the propagation of the electromagenetic radiation through the air. Later on we will discuss the influence of smoke or water vapor or solid materials. So we obtain an estimation of the received power. By answering the third question we demonstrate that an antenna is definitely not an ideal measurement device. We have to include its own temperature and its directivity pattern to calculate the output power. This output power is the most interesting quantity, since we have to process the antenna output signal to detect a fire. Moreover, by use of an antenna array instead of a single antenna we are able to scan the whole scenario and, therefore, we are also able to locate the fire origin within a certain resolution. To illustrate the whole problem – separated into three different questions – consider Fig. 1.

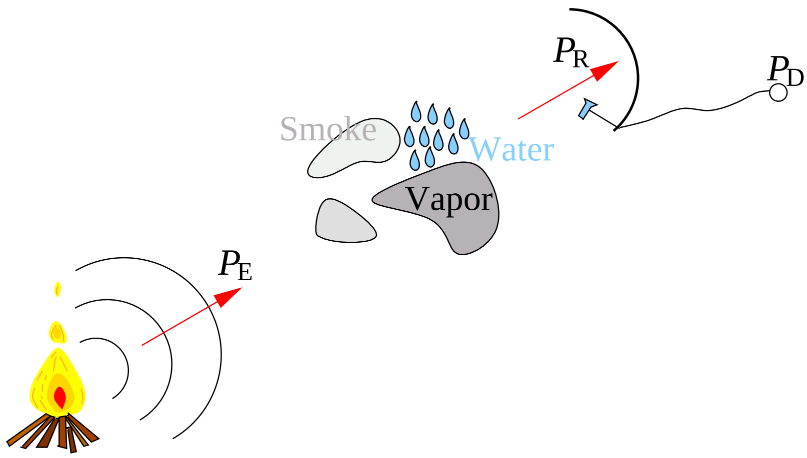

Figure 1: The emitted power P_E, the received power P_R, and the detected power P_D

2.1 How much MW-power P_E emits a fire ?

Consider an electromagnetic wave of frequency f which hits an arbitrary body with temperature T. The *power of the incident wave* is denoted as $P_I(f)$, whereas $P_{Refl}(f,T)$ is the

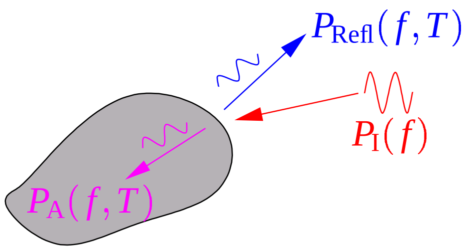

Figure 2: The incident power $P_I(f)$, the reflected power $P_{Refl}(f,T)$, and the absorbed power $P_A(f,T)$

reflected power, and $P_A(f,T)$ is the *absorbed power*. Note that the reflected as well as the absorbed power do not only depend on the frequency f of the incident wave but also on the temperature T. In general, they are also dependent on the direction of the incident radiation related to the surface of the body – the so-called *direction of arrival* – as well as to the polarization of the electromagnetic wave. Since here the latter two parameters are

more of random nature and thus we consider them as uniform distributed, we omit them as independent variables.
Let us now define the *degree of absorption* (or *absorptivity* for short) as

$$a(f,T) = \frac{\text{absorbed power}}{\text{incident power}} = \frac{P_{\mathrm{A}}(f,T)}{P_{\mathrm{I}}(f)}. \qquad (1)$$

Obviously, the range of the absorptivity is between zero and one ($0 \leq a(f,T) \leq 1$). An interesting body is such a one which absorbs all incident power irrespective of the frequency f and the temperature T. Such a body is called *black body* (remember how a *black* hole works) and is fully described by

$$a_{\mathrm{BB}}(f,T)) \stackrel{!}{=} 1, \quad \forall f,T,$$

where the index BB denotes the black body.
Let us leave the area of absorption and consider now the area of *emission*. If a body has a temperature greater than $T > 0\mathrm{K}$, it will emit radiation caused e.g. by a jump of an electron to a state of lower energy. In case of such a jump an electromagnetic wave occurs with energy hf, where $h = 6.626 \cdot 10^{-34}\mathrm{Ws}^2$ is PLANCK's constant. Consequently, each body with $T > 0\mathrm{K}$ radiates electromagnetic waves. Suppose that an arbitrary body emits the power $P_{\mathrm{E}}(f,T)$ than the *degree of emission* (or *emissivity* for short) is defined as

$$e(f,T) = \frac{\text{emitted power}}{\text{emitted power of a black body}} = \frac{P_{\mathrm{E}}(f,T)}{P_{\mathrm{E,BB}}(f,T)}. \qquad (2)$$

In contrast to the absorption we do not have an incident wave. Thus we need a reference quantity, where the black body emission $P_{\mathrm{E,BB}}(f,T)$ is a natural choice. Note that the emissivity of a black body is obviously equal to one. Note also that at this point we cannot state that the emissivity does not exceed the value 1. This will be shown later. In the following we try to find a relation between the emissivity $e(f,T)$ and the absorptivity $a(f,T)$ of an arbitrary body. For this reason consider Fig. 3. Suppose that the

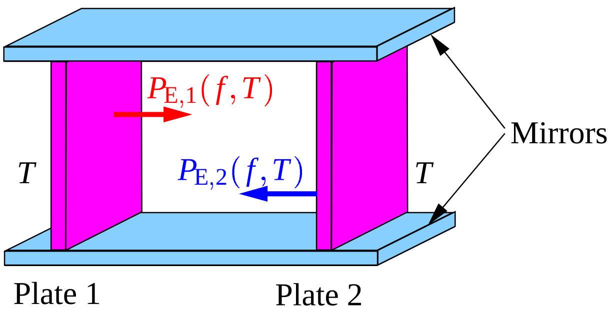

Figure 3: An experiment to find a relation between $e(f,T)$ and $a(f,T)$.

two plates are on the same temperature T. Each of them emit the power $P_{\mathrm{E},1}(f,T)$ or

$P_{E,2}(f,T)$. The plates are surrounded by two mirrors, so that no emitted radiation can be lost. Consequently, $P_{E,2}(f,T)$ is the incident power for the left plate whereas $P_{E,1}(f,T)$ is the incident power for the right plate. In other words, $a_1(f,T)P_{E,2}(f,T)$ is the absorbed power of plate 1 and $a_2(f,T)P_{E,1}(f,T)$ of plate 2, where $a_1(f,T)$ and $a_2(f,T)$ are the absorptivity of plate 1 and plate 2, respectively. Since we assume a thermical equilibrium – both plates have the same temperature T – both absorbed powers must be the same for each frequency and for each temperature

$$a_1(f,T)P_{E,2}(f,T) \stackrel{!}{=} a_2(f,T)P_{E,1}(f,T).$$

By use of eq. (2) we immediately obtain

$$\frac{a_1(f,T)}{e_1(f,T)} \stackrel{!}{=} \frac{a_2(f,T)}{e_2(f,T)}$$

where $e_1(f,T)$ and $e_2(f,T)$ are the emissivity of plate 1 and plate 2, respectively. Suppose that plate 2 is a black body then we get

$$\frac{a_1(f,T)}{e_1(f,T)} \stackrel{!}{=} 1$$

since for a black body the absorptivity and the emissivity are per definition equal to one. It follows for an *arbitray* body – here represented by plate 1 –

$$a(f,T) \stackrel{!}{=} e(f,T) \qquad \forall f,T. \tag{3}$$

This rule is called KIRCHHOFF's law and it means that an arbitrary body that absorbs much power also emits much power in the *same* band of frequencies. Of course, it can be a good absorber/emitter in one frequency band but a bad one in another.
We are now able to write the emitted power of an arbitrary body as

$$P_E(f,T) \stackrel{!}{=} a(f,T)\,P_{E,BB}(f,T). \tag{4}$$

Since the absorbtivity has a range $0 \leq a(f,T) \leq 1$ we are now able to say that the emitted power of an arbitrary body is always *equal to* or *less than* the emitted power of a black body. Thus, if we know $P_{E,BB}(f,T)$ we can use it as an *upper* bound for $P_E(f,T)$. Note that such a result is not clear by only use of the definition (2) for the emissivity. At that point we are not able to say that the emissivity is always less or equal to one.
The radiation $P_{E,BB}(f,T)$ of a black body was first derived by PLANCK, the founder of the *quantum theory*. Since the derivation is complicated we will here only give the final result, widely known as PLANCK's law

$$\frac{\mathrm{d}P_{E,BB}(f,T)}{\mathrm{d}f} = \frac{4\pi A h f^3}{c^2}\,\frac{1}{\mathrm{e}^{\frac{hf}{kT}}-1}, \tag{5}$$

where A is the bodies surface, $c = 3 \cdot 10^8 \mathrm{m/s}$ is the velocity of light, $k = 1.38 \cdot 10^{-23} \mathrm{Ws/K}$ is the BOLTZMANN-constant, and an emission in a half sphere is assumed (this means a solid angle of $\Omega = 2\pi$). Observe that the unit of $\mathrm{d}P_{\mathrm{E,BB}}(f,T)/\mathrm{d}f$ is W/Hz, so that it can be interpreted as the distribution of the power versus frequency. The following Fig. 4 shows this quantity as a function of the frequency for different temperatures and a body surface $A = 1\mathrm{m}^2$. It can be clearly seen that on the considered range of micro- and millimeter-

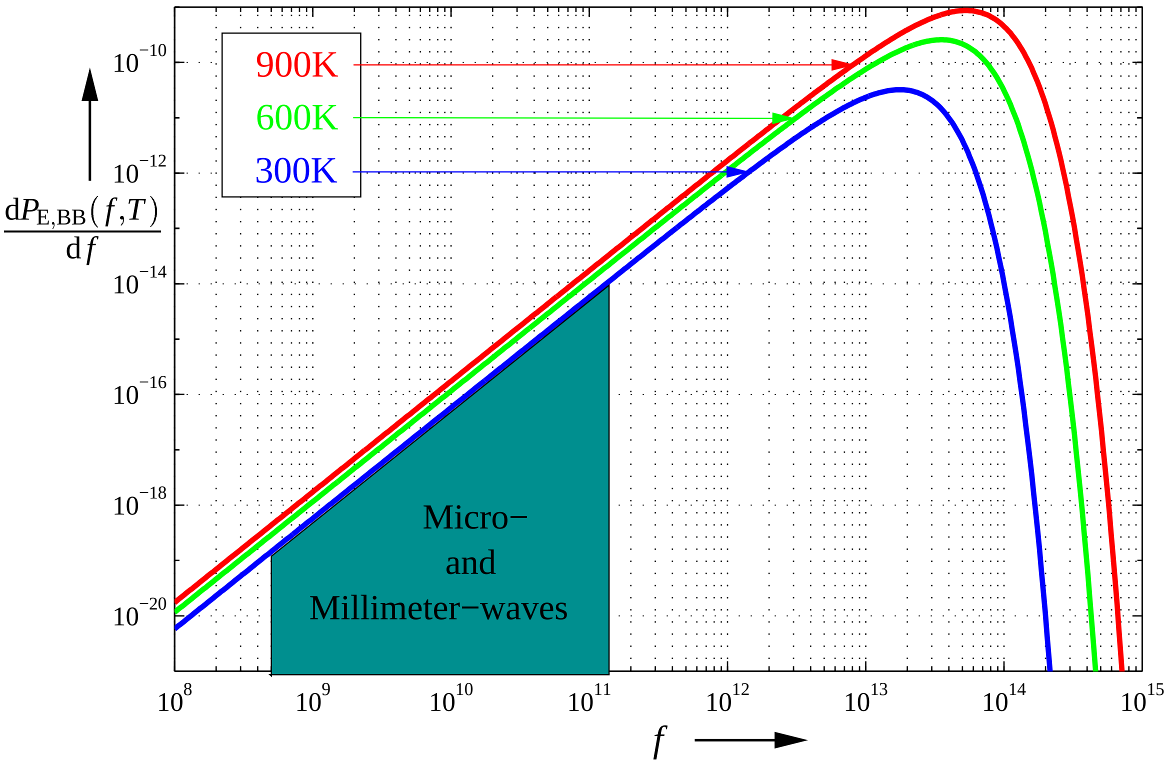

Figure 4: PLANCK's Law for $A = 1\mathrm{m}^2$

waves PLANCK's law can be approximated by a linear function in a logarithmic scale. The mathematical reason is that for such small frequencies the power series for the exponential function

$$\mathrm{e}^{\frac{hf}{kT}} = \sum_{n=0}^{\infty} \frac{1}{n!} \left(\frac{hf}{kT}\right)^n$$

can be broken off after the second term

$$\mathrm{e}^{\frac{hf}{kT}} \overset{hf \ll kT}{\approx} 1 + \frac{hf}{kT}.$$

We obtain

$$\frac{\mathrm{d}P_{\mathrm{E,BB}}(f,T)}{\mathrm{d}f} \approx \frac{4\pi A f^2 kT}{c^2}, \tag{6}$$

which is a linear function in a logarithmic scale. This result is known as the law of RAYLEIGH-JEANS. The advantage of eq. (6) is the possibility for an integration in a closed form. Denoting f_c as a *center frequency* and Δf as the considered *bandwidth* the total emitted power can be calculated as

$$\begin{aligned} P_{E,BB}(f_c, \Delta f, T) &\approx \int_{f_c-\Delta f/2}^{f_c+\Delta f/2} \frac{4\pi A f^2 kT}{c^2} \mathrm{d}f \\ &= \frac{4\pi AkT}{3c^2}\left(3f_c^2\Delta f - 2(\Delta f/2)^3\right) \qquad (7) \\ &\overset{f_c \gg \frac{\Delta f}{\sqrt{12}}}{=} \frac{4\pi AkT}{c^2} f_c^2 \Delta f \qquad (8) \end{aligned}$$

We have now obtained an equation for the transmitted power of a black body depending on the user-chooseable center frequency f_c, the user-chooseable bandwidth Δf, the surface A and the temperature T of the black body. To get a feeling about the range of this power consider a practical scenario. Suppose a surface of $A = 0.5\mathrm{m}^2$, $T = 1000\mathrm{K}$, $f_c = 11\mathrm{GHz}$, $\Delta f = 1\mathrm{GHz}$, then the emitted power is equal to $P_{E,BB}(11\mathrm{GHz}, 1\mathrm{GHz}, 1000\mathrm{K}) = 116.24\mathrm{nW}$ which is easy to detect with conventional antennas. Of course, here we have not only omitted the absorptivity $a(f,T)$ but also the distance r between the antenna and the fire. Before we explain how to include r we will finish the first question by a short discussion about $a(f,T)$.

From PLANCK's law it can be seen *that only the surface A* of the black body influences the emitted power. It is also known that microwaves or also millimeter-waves can travel through solid material with sometimes only a small attenuation. This is in contrast to IR-radiation which is clearly attenuated by solid materials. Thus, we might expect that in case of MW-radiation not only the surface but also the inner of a real body (e.g. the fire) will contribute to the emitted power. Since the black body radiation does only depend on A the absorptivity $a(f,T)$ must exhibit a corresponding behaviour. In other words we have to expect – as a tendency – that $a(f,T)$ must be higher for MW-frequencies than for IR-frequencies. Moreover, this tendency must be valid for all temperatures. Therefore, it might be very interesting to measure the absorptivity $a(f,T)$ of typical fire materials (e.g. wood). This is planned for a future research project. To get a feeling about the quantity of absorptivity and equivalently of the emissivity, consider the following tabular (see [1]). Although these are *not* materials typically occuring in fire detection it shows that the values for the absorptivity and emissivity are not very small. Of course, one exception is *metal* which totally attenuates electromagnetic radiation due to the huge number of free electrons. So, the emissivity as well as the absorptivity are nearly zero for metal.

After we have answered the question *How much MW-power P_E emits a fire ?* we can say that a detection of a fire by measurement of MW-radiation seems to be possible if all radiation near f_c can be collected. However, this would mean that around the fire an

Material	$e(30-90\text{GHz}, 280\text{K})$	Material	$e(30-90\text{GHz}, 280\text{K})$
Sand	0.90	Smooth rock	0.75
Asphalt	0.83	Concrete	0.76
Coarse gravel	0.84	Heavy vegetation	0.93

Table 1: Typical emissivity for normal incidence and 280K

half sphere have to be constructed which fully works as an antenna. Since this is a very unpractical approach we have to ask the second question:

2.2 How much MW-power P_R receives an antenna ?

To explain the principal problem consider Fig. 5. We assume that a fire *omnidirectionally*

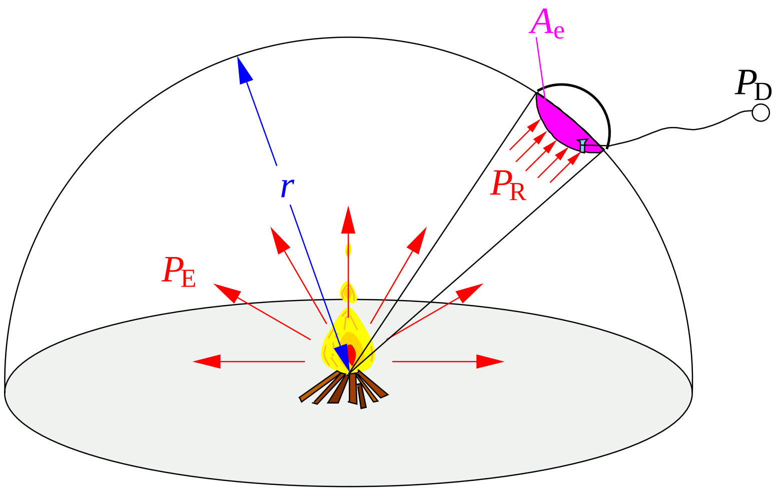

Figure 5: A practical setup

emits its radiation in a half sphere so that each point on the half sphere receives the same amount of radiation power. Since a half sphere has a surface of $2\pi r^2$ we immediately obtain for the received power

$$P_R(f,T) = \frac{A_e}{2\pi r^2} P_E(f,T), \tag{9}$$

where A_e is the so-called *effective area* indicated in Fig. 5 directly beneath the antenna as a patterned region. We will not discuss the details of the idea of the *effective area*. For a short explanation consider an antenna of reasonable size and regular shape, e.g. a satellite dish. Then the effective area is nearly equivalent to the geometrical surface of the parabolic mirror. It should be pointed out that the effective area does only depend on the antennas shape and *not* on the received radiation. We emphasize this fact because in the literature the relation $A_\mathrm{e} = \lambda_\mathrm{c}^2 G_\mathrm{e}/(4\pi)$ can often be found. Here $\lambda_\mathrm{c} = c_0/f_\mathrm{c}$ is the *center wavelength* and G_e is the so-called *antenna gain*. Since the antenna gain is often given as a number (e.g. for a $\lambda_\mathrm{c}/2$-dipole $G_\mathrm{e} = 1.64$), we might assume that the *effective area* becomes quadratically dependent on the carrier frequency. This might cancel the increase of $P_{\mathrm{E,BB}}(f_\mathrm{c}, \Delta f, T)$ on f_c^2 in eq. (8) so that the received power $P_\mathrm{R}(f,T)$ would not longer depend on the center frequency. This is not true, since the antenna gain *is* frequency dependent and the effective area *is not*.

Thus, it follows from eq. (9) that the received power decreases inversely proportional to the square r^2 of the distance r and increases linearly with the antennas effective area. Suppose that a measurement of picowatts is possible with a satellite dish. Assume that the parabolic mirror has a diameter of 80cm. Then we obtain for the maximum distance between the antenna and the fire in our practical example

$$r_{\max} = \sqrt{\frac{\pi(0.4\mathrm{m})^2 P_\mathrm{E}(11\mathrm{GHz}, 1\mathrm{GHz}, 1000\mathrm{K})}{2\pi\, 10^{-12}\,\mathrm{W}}} = 96.43\mathrm{m}.$$

Such a maximum distance might be sufficient in numerous applications. However, note that the maximum distance is linearly depending on the center frequency f_c so that it can be increased if needed.

Up to now we do not have considered a possible attenuation during the propagation of the electromagnetic wave from the fire to the antenna. In other words we have assumed a free space between fire and antenna. So, let us fill this free space with some material, e.g. air, fog, smoke or a solid. Of course, we will have some additional attenuation which depends on the emitted frequency f as well as the temperature T and may be also on other parameters, e.g. the humidity of the material. Hence, we have to extend eq. (9) as follows

$$P_\mathrm{R}(f,T) = |H(f,r)|^2 \frac{A_\mathrm{e}}{2\pi r^2} P_\mathrm{E}(f,T), \tag{10}$$

where $H(f,r)$ is the transfer function from the fire to the antenna (or vice versa) for a given frequency f and distance r. In general, suppose that a source emits a signal $s_e \sin(2\pi f t)$ with a constant amplitude s_e. This signal propagates through the considered material, e.g. air, fog or smoke, over a distance r and a sink receives the signal $s_r(f,r)\sin(2\pi f t + \phi(f))$ with a frequency dependent amplitude $s_r(f)$ and an arbitrary phase $\phi(f)$. Then the transfer function is simply given by

$$H(f,r) = \frac{s_r(f)}{s_e}\, \mathrm{e}^{-\alpha r}\, \mathrm{e}^{\mathrm{j}\phi(f)}$$

where $\alpha \in \mathbb{R}$ includes the properties (particle size distribution, optical index of refraction) of the considered material and the received amplitude $s_r(f,r)$ can be separated as

$$s_r(f,r) = s_r(f)\, \mathrm{e}^{-\alpha r}.$$

The next figure shows the attenuation $10\log|H(f,1\mathrm{m})|^2$ in dB/m in case of air and fog. It can be seen that the attenuation in case of air is strongly fluctuating. This is due to the

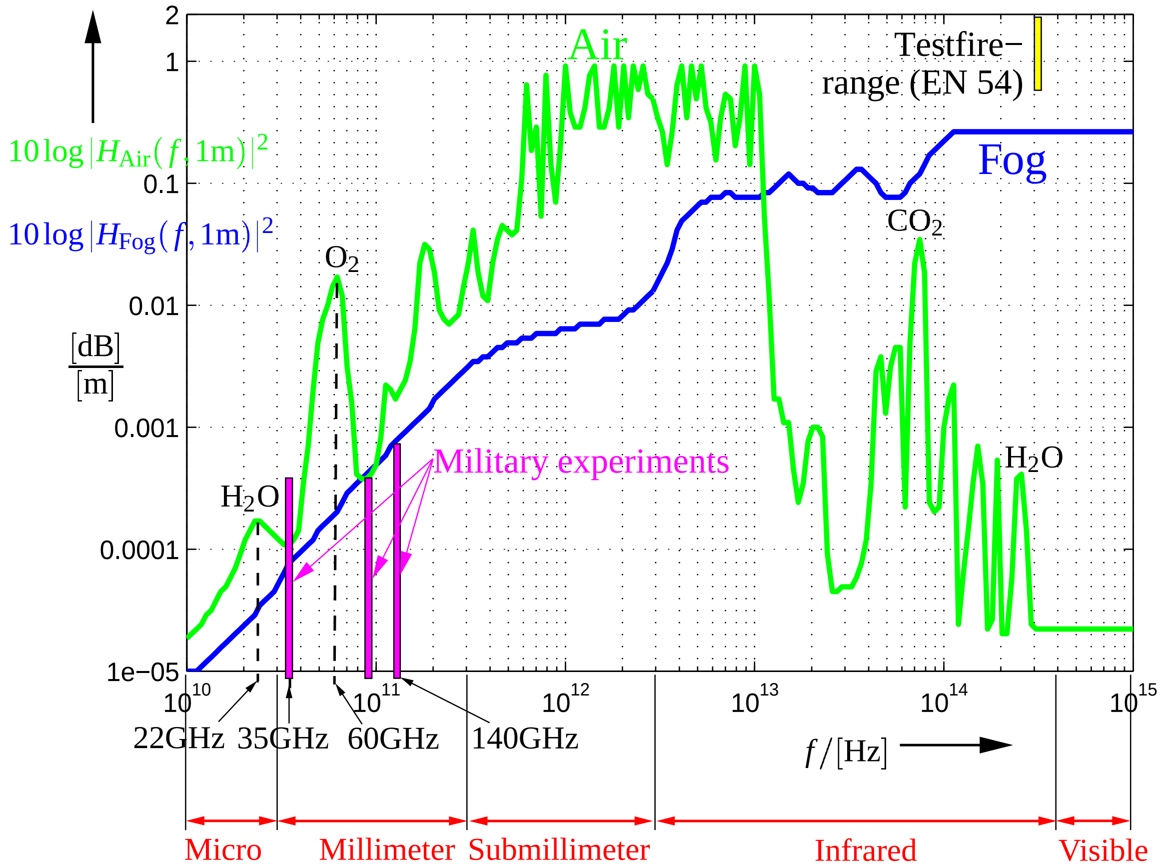

Figure 6: Attenuation of Air and Fog

molecules in the air, like e.g. O_2 or H_2O, which absorb energy in certain frequency bands leading to a high attenuation. This must not be necessarily a disadvantage. For example in future generations of wireless communication a carrier frequency of 60GHz might be chosen to achieve small communication cells.

Comparing the MW- to the IR-region it can be also seen that the IR-region exhibits numerous window frequencies whereas the MW-region shows a principal increasing behaviour with increasing frequency. This means that for MW the considered center frequency f_c should not be too high which is in contradiction to the result we found in eq. (7) or (8), where the center frequency should be as high as possible to increase the emitted power. In other words, here a compromise has to be found in future.

The other curve – *fog* – shows not only a more smooth behaviour, but, much more interesting, it demonstrates that IR-radiation is *clearly attenuated* whereas the attenuation of MW-radiation nearly *remains unchanged*. Therefore, the MW-radiation power of a real body might become to a similar order of magnitude as the IR-radiation power for fog or,

more interesting, *smoke*. Although this result is surprising, it is further confirmed by the former discussion that for MW-radiation not only the surface of the burning material but also the deeper layers are contributing to the total emitted power. Moreover, it can be seen in Fig. 6 that according to the EN 54 (European Standard) all of the smoke generating test fires are leading to an attenuation *greater* than fog in the IR-domain around 300THz (corresponding to a wavelength of approximately 900nm). We have indicated well-known typical values of 0.6dB/m (open wood fire) to 2dB/m (smouldering woodfire (pyrolysis), glowing smouldering fire (cotton)) for these test fires. To our best knowledge only a few things are known on the attenuation of MW-radiation in case of smoke (see [2]). The experiments were done by the military (fog oil, dust dispersed by detonating high explosives, white and red phosphorous packages). For the window frequencies 35GHz and 94GHz only the dust experiments – not the smoke experiments – have shown an attenuation of 0dB/m to 0.000375dB/m. At 35GHz the maximum attenuation is a little bit increased to 0.0005dB/m. These results are also shown in Fig. 6. as three filled bars. Thus, in case of a smoke caused by a fire we expect only a very small attenuation so that the MW-radiation approach might be prefered in comparison with existing IR-Radiation based techniques. In conclusion we can state that more research is needed about the attenuation of MW-radiation for fire detection.
After answering the second question we ask the last question:

2.3 How much MW-power P_D detects an antenna ?

The remaining task is now to construct an almost ideal antenna which converts the received electromagnetic radiation P_R in an electric power P_D as optimal as possible. Here we are faced with two principal problems:

1. The antenna will also receive other radiation not caused by the fire.

2. The antenna itself introduces additional noise due to their imperfectness.

Concerning the first problem, it is clear to suppress as much as possible of the undesired radiation. This leads to the question – What is the cause of undesired radiation ? Of course, each antenna has a directivity pattern which shows to which extent an incident wave under angle ϕ is amplified. For example, a satellite dish exhibits a high directivity in one direction – the so-called *main lobe* – whereas other directions (side lobes) are mainly suppressed. However, if a small fire is propagating and even if the main lobe is directed to the fire, then the antenna will also receive additional radiation caused by other heat sources. These other sources are simply some material, e.g. the wall of the closed room, for which the temperature is higher than 0K. Thus, in practice we have to expect a lot of distortions. For this reason it is very important to develop an antenna with a very narrow beam and very low side lobes. We will not further discuss this task since this is outside the scope of this paper. However, even if we have developed such an antenna, how can we achieve that its main beam is always pointed directly to the fire ? This problem can be solved by the so-called *smart antennas* known from wireless communications or radar processing. Smart antennas are usually consisting of an *array* of antennas where all the antenna outputs are processed together to steer the main beam of the whole antenna array in a certain direction. In other words, the antenna array is able to *scan* the environment. Of course, this scanning leads to a *picture* which shows the temperature profile of the environment. This picture could be for example displayed on a screen so that a fireman entering a smoked room could be able to locate the fire. Moreover, since the antenna array scans the whole environment, the resulting temperature profile might show – beside the fire location – also people in danger. The following figure shows the principal setup for a non-mobile situation.

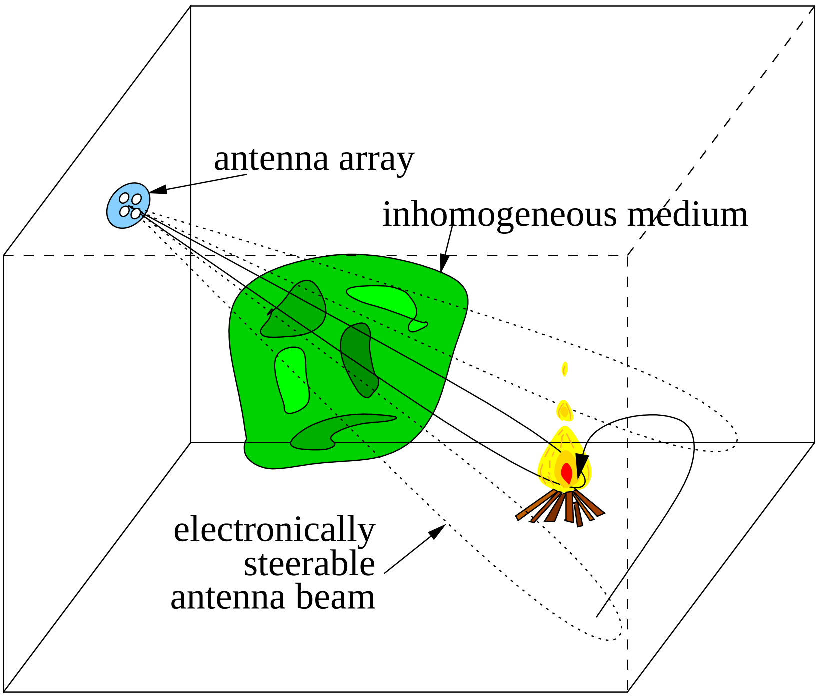

Figure 7: An antenna array to estimate the location of the fire origin.

Now let us consider the second problem. Since the antenna will also exhibit a temperature of higher than 0K, it will introduce some additional thermal noise in our measurement. In addition, all successive amplifiers will decrease the precision of our measurement due to additional thermal noise. Fortunately, a very clever approach is known to suppress at least the noise caused by the amplifiers. This principle is called DICKE-radiometer and it works as follows. The antenna output signal and a signal of a reference object of *variable*

temperature T_r are the inputs of a switch – called the DICKE-switch. The output of the switch is connected with an amplifier circuit so that the output of this circuit is used to measure the incident radiation power. The switch will be periodically switched, e.g. with a frequency of 1kHz. During the measurement the temperature of the reference object will be varied until the output power of the whole amplifier circuit remains constant. So the output power will be independent of the switching cycles. In this case we can determine the temperature of the received radiation – it is simply equal to T_r in this case – and due to PLANCK's law also proportional to the power of the received radiation. Consequently, the thermal noise of the amplifiers will not affect our measurement if we successfully apply the DICKE-approach.
In this subsection we discussed the main problems and gave an approach how it could be possible to solve them. Of course, much work is still needed to find an optimal antenna configuration for the desired purpose. In the last section we will show the first results obtained by some experiments in the fire detection laboratory of GERHARD-MERCATOR-University Duisburg, Germany.

3 Some first experiments

The first experiments for fire detection in garbage bunkers with microwaves were done by DASA (DaimlerChrysler Aerospace AG). Their results have motivated us to investigate this idea more detailed. In contrast to IR-radiation the MW-radiation seems not only to be technically unused in fire detection but also it seems not to be measured for standardized test fires (TFs). For this reason some first experiments were done at the fire detection laboratory of GERHARD–MERCATOR–University Duisburg.
We have used a commercial satellite dish and a low noise converter (LNC). The dish was adjustable in space so that either the MW-radiation of the room walls or of the fire was measured. The center frequency was $f_c = 11$ GHz and the chosen bandwidth was $\Delta f = 1$MHz.
In the first experiment charcoal of an area of $0.15\,\mathrm{m}^2$ was ignited with a distance to the antenna of $r = 4$ m. The measured power difference was fluctuating between $0.4 - 0.6$ dBm. To study the principal effect of smoke we have blown some water vapor between the antenna and the fire. The maximum loss in power was 0.05 dBm compared to the smokeless situation. To get a more detailed picture we have carried out most of all test fires according to the European standard (EN 54), where now the distance between the antenna and the fire origin was increased to nearly the maximum possible of $r = 7$ m. We have obtained the following results.
All fires containing some glowing material (TF1, TF2, TF4) can be easily detected. In

Test fire	typical behaviour	power gain	remarks
TF 1 - open wood fire	flames and later glowing wood	0.6 dBm	embers were measureable, flames were not measureable
TF 2 pyrolysis	much smoke and later glowing wood	0.15 dBm	smoke has no influence, embers were measureable
TF 4 - open polyurethan fire	smoke, flames and embers	0.15 dBm	increased power level probably due to embers
TF 5 - liquid n-Heptan fire	flames and high temperature	0 dBm	no change
TF 6 - liquid spirit fire	flames	0 dBm	no change
TF 7 - dekalin fire	flames, dark smoke, low temperature	0 dBm 0 dBm	neon tube behind the fire can be easily detected

Table 2: Results of the test fires

contrast, fires only consisting of flames (TF 5, TF 6, TF7) cannot be seen. This is not surprising since a flame has spectral components mainly in the IR- or visible light-region. However, flames are not in our focus since sophisticated flame detectors are already developed to reliably solve this detection problem [3]. To get a first impression of the influence of smoke we have arranged behind the test fire TF 7 a neon tube. Despite the optical dark smoke the neon tube can be easily detected by its MW-radiation. As a consequence, the assumption that smoke only slightly attenuate the MW-radiation is confirmed by this example.

4 Conclusions

In this paper we presented the fundamentals of microwave radiation for fire detection. MW-radiation offers some distinct advantages in comparison with conventional IR–radiation. For example, MW-radiation penetrates also optical thick smoke and vapor with only a slight attenuation and it penetrates principally all materials except metals. Moreover, MW-radiometers are very insensitive to environmental conditions, such as water vapor and dust (contrary to infrared methods) and high temperatures (contrary to semiconductor sensors). Last but not least, thermal microwave noise radiation comes from a *thicker surface layer* than does IR radiation. In contrast, two main disadvantages concerning fire detection can be given, first, with increased center frequency the costs are clearly increased, and second, because of the relatively long wavelengths compared to IR, the achievable spatial resolution might be limited.

We have also derived a closed formula for the received antenna power. This formula shows the influence of chosen parameters, like the antenna bandwidth, the antenna effective area and the antenna center frequency and of non-chooseable parameters, like the temperature of the fire, the distance between fire and antenna, and the surface of the fire.

By some first experiments we have demonstrated that with a very simple setup – a commercial satellite dish – fires can be easily detected if the burning material is glowing. In our opinion much research is needed on this area, since many applications can be imagined where microwaves are very useful for fire detection.

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